Comparative Study of Different Inter-laminar Strengthening Techniques

D.Muruganandam, J.Jayapriya, M.K.Karthik, S.Suraj

***Abstract*: Composite materials has found itself a huge role in the aircraft industry. Though composite comes with a lot of advantages it has its own drawbacks. One such drawback in composite laminates is the low interlaminar strength which affects the performance of composites. In this paper we try to gain knowledge about the various techniques that have been developed over the years to overcome this drawback, so that the strength of composites can be improved which makes them to be used at critical places in aircraft also. Efforts have been made to study the principle behind techniques like z-pinning, 2D and 3D woven composites, polymer additive manufacturing and addition of carbon nano- tubes.**

***Index Terms*: z-pinning, polymer additive manufacturing, woven composites, carbon nano-tubes.**

I. INTRODUCTION

Composites in general is prepared from two or more different materials which has significant physical and chemical properties which combined will produce a composite which has characteristics varying from all the individual parts. However materials individually will remain separate and distinct even when it is a composite.

The usage of composites remains in the history from 1500 B.C. People who have settled in the places of Mesopotamian as well as Egypt used a combination of straw and mud to make strong as well as long lasting building structures. Straw from plants remained as the major reinforcement in ancient composite products which typically include pottery and boats.

During the later periods of 1200's warriors from Mongol army had archery bows crafted from composite materials namely bamboo, cattle tendons, horns, pine resin etc., which were swifter and more powerful than those of their rivals: The bows had tendons on outer side which produced tension side and at the same time horn sheets on inner side which produces compression over a core of bamboo. The entire bow was wrapped tightly with silk and enclosed inside pine resin.

With the end of world war II many of greatest advancements started to begin in the field of composites. This marked the beginning of seeing composite material as commercial product with mass production rather than being an object meant for laboratory research. Materials other that steel and aluminium were needed to be replaced by the lightweight materials mainly for the military aircraft. Engineers came out with composites which was mainly lightweight and strong.

Generally failure in composite structures happening at macroscopic scale leads to significant changes in the physical structure. These change are the manifestation of large number of "micro-failures"which collectively leads to the macroscopic failure. The material behavior during these conditions will be highly non – linear.

The main objective of using resin is to create a bond between the adjacent layers of laminates which binds the laminate. The transfer of displacement will be happening from one layer to the adjacent layer through this resin. When the resin gets damaged due to some reason this interface between the layers gets weakened or gets damaged completely which ultimately leads to the separation of adjacent layers. This type of failure mode in laminates is so often named as delamination.

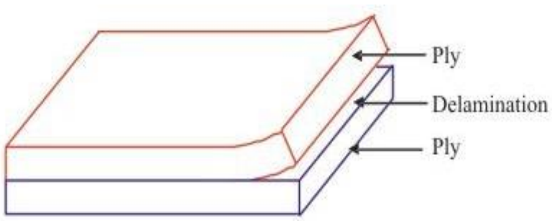

Figure1.Macro-level damage mechanism - Delamination.

The effect of delamination is reduced strength combined with stiffness which finally affects the life of given structure. Also stress concentration occurs at load bearing plies and delamination grows due to local resulting in compressive failure of laminate. In both the cases delamination redistributes the structural load paths precipitating the structural failure. Therefore, delamination indirectly paves way for the final failure of the structure reducing the shell life. It can be concluded that delamination is the most prevalent life limiting damage mode.

II. INTERLAMINAR STRENGTHENING TECHNIQUES

A. *Z-Fibre Pinning:*

Z-fiber pinning is process of inserting reinforcing fibers directly in the direction of thickness of the laminate. In models used for analysis purpose, the through-the-thickness coordinate is often designated as "z-axis". This paves the name "z-fibers" since the fibers remains oriented in the direction of z-axis.

The process of z-fiber reinforcement is iniated by keeping a release film followed by z-fiber preform and finally rigid tool onto the already laid-up prepreg laminate. z-fiber preform is made up of structural foam which contains the fibers used for reinforcement. The whole of the arrangement is placed in vacuum bag inside

Revised Manuscript Received on May 03, 2019.

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a autoclave subjected to standard curing cycle. The temperature in the autoclave softens the preform which ultimately collapses due to pressure applied. The z-fiber reinforcement is finally driven into laminate.

Once taken out from the autoclave, the cured foam is dismantled and taken for further usage . The final product is achieved by removing any extra pin material which keeps projecting out from the laminate. The Z-fiber preforms are fabricated using retrofitted insertion machine which embeds reinforcing fibers into structural foam. The insertion machine is programmable which can insert z-fibers at any comfortable lengths, spacing and patterns.

A variety reinforcing materials can be used which includes pan as well as pitch based carbon/epoxy, carbon bismaleimides, glass/epoxy, titanium, refractory alloys and stainless steel. The reinforcing fibers shall be having diameters in the range of 0.15 mm to 1 mm.

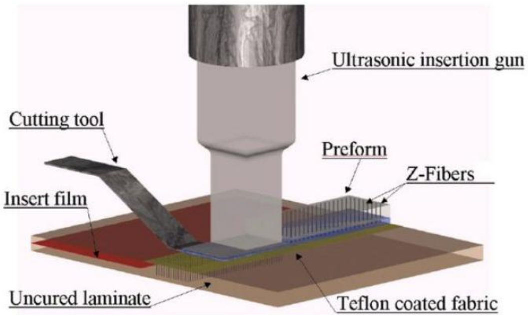

Figure 2. Fabrication of z-pinning laminates.

Different method of inserting Z-pins are available as on date. One such method employs the use of ultrasonic hammer which pushes the Z-pins into the uncured preform by inducing high frequency vibrations and transferring the same to the pins. This vibrating chamfered tip of the Z-pins creates heat locally which softens the resin paving way for Z-fiber to be penetrated into preform having minimal disruption of original long fibers.

The process of Z-fiber pinning helps to improve resistance against the impact at low velocity. Pinning also shrinks the area damage due to impact by around 64% owing to the thickness of the sample as well as impact energy in the laminates. It can be evaluated that pinning get more effective when the specimens gets thicker as well as impact energy becomes high.

Z-pinning also improves the property of compression post impact strength by 45% in comparison with the unpinned components. The CAI strength is found to be independent of specimen thickness and impact energy. The z-fibers provides increase in design strain limit for aircraft structures by about 50 %.

B. Woven Fabric Structures:

2D woven composite fabrics are those made by the process where two yarns are interlaced together. The two yarns are named as follows: warp and weft. The warp and weft will be running in cross direction i.e., 90 degree. The warp yarn will be twisted in structure and comparatively stronger than filling yarns, Weft yarns are also called as “filling yarns” and “picks”. 2D woven composites are well known for resistance against impact damage. Sometimes the warp and weft yarns needs to be bend for one yarn to pass over te other yarn. Such a condition is called as crimp. This presence of crimp will affect the mechanical properties of 2D woven composites.3D weaving differs from 2D weaving by containing extra additional “z-yarn” which acts as binder throughout the thickness of 3D woven fabric.

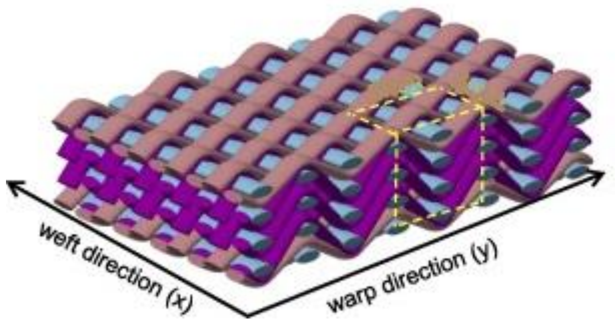

Figure 3. Directions of fiber in woven composites

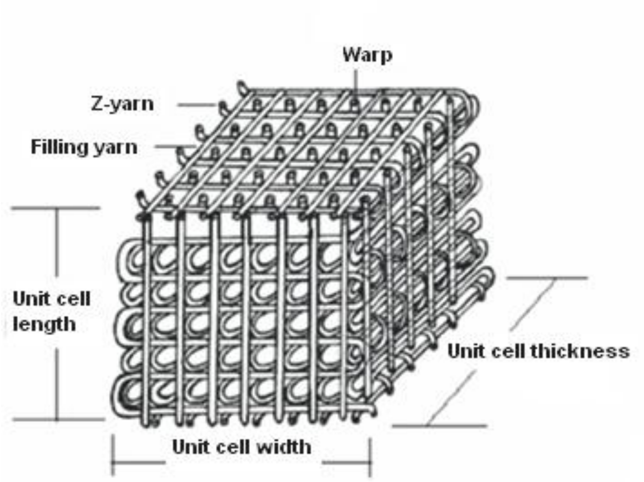

Figure 4. 3D woven composites with z-yarn.

While fabricating 3D woven composites, z-yarn will make the specimens to look solid by interconnecting the warp and weft yarns throughout the thickness. Angle interlock, orthogonal weave and multilayer techniques are widely used 3D structures which has usage in impact and ballistic resistance components because of its high delamination resistance in comparision with the normal laminated composites.

3D woven composites prevents the damage due to impact by its unique energy absorption mechanisms which prevents the failure by spreading the area of damage to large extent in case of low velocity impacts. The unique energy absorption mechanism will distribute the impact force along the fibers so as to withstand the penetration due to impact.

The reason for 3D woven composite to possess excellent impact resistance is that no delamination will occur, due to the existence of z-yarns in thickness direction.

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Delamination occuers in 2D woven composites when subjected to impact because the crack will propagate till it reaches the interface of adjacent ply which has different fiber orientation as the energy increases. Thus, delamination process starts when the matrix cracks not propagating in the intended direction and often gets deviated towards the adjacent ply interface.

The delamination process actually takes place in three different stages. It starts with "critical matrix crack" where the matrix will start to crack which ultimately initiates the process of delamination. It is immediately followed by "delamination" the process in which the crack propogates beyond the adhesion layers. Finally it leads to "micro matrix cracks" condition in which transverse matrix cracks appears as process of delamination continues.

z-yarn is created when the warp yarn is going from top to bottom layer. This yarn will bind all the layers together which will enhance the structural integrity. Damage resistance due to impact will be greater as well as there will be lower in-plane mechanical properties of 3D woven composites compared to 2D composites.

B. *Polymer Additive Manufacturing:*

The matrix will be present in the region which is formed between adjacent layers in the layered composite. This matrix region will be mostly weak which renders the laminate to be vulnerable for delamination mode of failure. It is evident that interlaminar stresses will be significantly high at free edges of multi-directional laminated composites. This is mainly due to property mismatch between various layers. This phenomenon is often termed the "free edge effect", which often initiates delamination failure in laminates.

Polymer additive manufacturing refers to the process of introducing structural reinforcements at the inter laminar region which improves the inter laminar strength and toughness of the laminate. This process has the freedom for making complex design patterns with ease, which proves to extremely useful while imparting spatially modified smart designs at the interlaminar spaces in laminates.

Using the fused deposition modeling technique Reinforcements can be imposed onto carbon fibers for imparting interlaminar modifications. The Inter laminar shear strength values of such laminates with transformed interlaminar regions results in increase of strength by approximately 28%. This same can be achieved by the introduction of additional resin other than the one normally used which are present at interlaminar regions which has printed reinforcements.

It can be inferred that increase in number of changed interlaminar regions results in insufficient pre-existing resin in the prepreg used for wetting the printed reinforcements which ultimately results in unnecessary voids. Hence, excess resin is necessary for altering the structure of interlaminar regions in a laminate.

The rise in Inter Laminar Shear Strength with modified design is mainly due to resistance given by printed reinforcements which means the fresh surfaces generated due to delamination while conducting short beam shear tests were undulated in the fresh laminates as against the smooth region in pristine samples. Such properites corroborates the resistance against delimitation offered by printed reinforcements.

It may be obsered that printed reinforcements will increase overall thickness of laminate, which can be optimized by having fine patterns at interlaminar regions by employing 3D printers having finer print nozzles.

C. *Carbon Nanotube Additions:*

Low stress or strain thershold limit for damage initiation in case of composites has been a major drawback for extensive use of composites for variety of applications. For example the carbon fiber reinforced epoxy composites, subjected to static tensile loading will experience the first matrix cracks in case of cross-ply (0/90) or quasi-isotropic laminates at strains as low as 0.4%, the same in case of woven textile composites may be as low as 0.2%, however the final failure strain may go upto the range of 1.5 to 2%.

Over the Last decade the science community has been doing research in the field of Carbon nanotubes (CNTs). The main reson behind this growth is the excellent mechanical properties which may replace carbon fibers as reinforcement in the near future. However the drawback is such advancement is its nanometer size, which will enable defect free tubular graphene structure.

By using CNT as "fillers" for polymers, the maximum volume fraction will be limited to a fewer percentage.

However these type of structures can be used in placed where polymers are used under electrically conductive enviroment and mechanical properties does not play a major decisive role in the functioning of the structure.

To achieve high strength and stiffness using micron-sized carbon fibers, processed using the 'traditional' PAN-based manufacturing process, will be easy when compared with the carbon nanotubes which are manufactured using the CVD or arc discharge process.

To overcome this issue, carbon nanotubes are used as additional reinforcement in the glass and carbon fiber composites. Hence, two-level reinforcement terminology comes into picture, Laminates fabricated by this process can be termed as 'nano-engineered composites'.

Fiber-matrix interface is the key point which facilitates the transfer of load thorugh the laminate which prevents the failure of the structure. Carbon fibers in general has good properties in this regard. The carbon fibers in generall does react chemically easily and will have have poor wettability issue hence cannot have good adsorption property with matrix material.

To overcome the above mentioned drawbacks methods are available such as surface treatment of fibers which either create chemical bonding on surface (leading to more adhesion with the matrix) or make the surface to be rough (by providing mechanical key between resin and fiber) or a combination of both, ultimately leading to create more bond with the matrix. In most of cases both effects are made to happen simultaneously.

The above mentioned methods to improve the bonding between fiber and matrix often results in significant reduction of fiber strength which becomes a major drawback. Also, the techniques are complex working processes (e.g., treatment by acids/alkalis/ strong oxidization agents etc.) or needs usage of expensive infrastructure, which rises the total expenditure of the treatment significantly.

Carbon fibers when treated with Rare earth salt (RES) is a trend which is recently upcoming. As per the suggestions of chemical bonding theory, when the RES is adsorbed on carbon fiber as well as any polymer surfaces by the process of chemical bonding will increase the concentration of reactive functional groups which is the inherent property of rare earth (RE) elements.

The interfacial adhesion can be increased when these reactive functional groups improves the compatibility of carbon fiber and matrix. RES is also having the capability to form coordinate and ionic bonds with many functional polymer group and carbon fibers.

III. CONCLUSION

An effort has been made to study the various techniques that are available to improve the interlaminar strength. Though we have made a comparative study, the same has to be verified through conduct of experiments to understand the actual improvement in the properties in laminates.

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